AIP | Review of
Scientific Instruments

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Citation: Rev. Sci. Instrum. **75**, 3828 (2004); doi: 10.1063/1.1783607
View online: http://dx.doi.org/10.1063/1.1783607
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v75/i10
Published by the American Institute of Physics.

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 75, NUMBER 10 OCTOBER 2004

Improvement of the T_e profile on Joint European Torus measured by electron cyclotron emission

Patrick Blanchard[a)]
Association Euratom-CEA, DSM-DRFC, CEA Cadarache, 13108 St. Paul lez Durance, France

Elena de la Luna
Asociación EURATOM-CIEMAT, Laboratorio Nacional de Fusión, Madrid, Spain

Chris Gowers
Association EURATOM-UKAEA Fusion, Culham Science Centre, Abingdon, United Kingdom

JET-EFDA contributors

(Presented on 20 April 2004; published 7 October 2004)

On the Joint European Torus (JET), a key source of calibrated electron temperature T_e profiles is from the measurements of the full electron cyclotron emission (ECE) spectrum made by a Fourier transform spectrometer (FTS). It is absolutely calibrated by using a calibration source inside the vacuum vessel. High spatial and temporal resolution ECE T_e profiles are obtained using a 96-channel heterodyne instrument which is cross-calibrated on each JET pulse against the data from the FTS system. Residual systematic frequency dependent errors at the 5%–10% level can then be evaluated and corrected for, using specific discharges in which the toroidal field is varied while keeping the shape of the T_e profile constant. This improvement in the calibration method has been systematically applied at JET for the first time improving both the smoothness and the symmetry of the T_e profiles. The consequences of this improvement are discussed. In addition, it is shown that no deviation occurs in the FTS calibration for more than eight years, which is relevant for the International Thermonuclear Experimental Reactor.

[DOI: 10.1063/1.1783607]

I. INTRODUCTION

In fusion devices, the accuracy of electron temperature T_e obtained with electron cyclotron emission (ECE) measurements is dominated by the uncertainties during the calibration process. On the Joint European Torus (JET), absolute calibration is done by filling the antenna pattern of the diagnostic's antenna with generally two sources of known temperature and emissivity. The intensity of the existing sources being about five orders of magnitude lower than the plasma emission, the calibration procedure requires many hours of coherent integration to recover the signal from the detector noise. Experience at JET[1] shows that the residual noise in the calibration data leaves systematic uncertainties in the absolute level of the measured response, i.e., of the level of the measured temperature, of about ±10%. The uncertainty on the frequency dependence and, therefore, the uncertainty on the shape of the T_e profile, is believed to be about 5%. The main effect of such systematic uncertainties is the appearance of typical features on the T_e profiles, such as oscillations or asymmetries at specific magnetic fields. As the errors are fixed in frequency, it is possible to improve the relative amplitude of the calibration factors doing specific discharges with a toroidal field ramp (TFR).[2] Such corrections have been systematically applied at JET for the first time. The effect of the application of this method on T_e JET profiles and the consequences of the corrections are discussed in this article.

II. JOINT EUROPEAN TORUS ELECRON CYCLOTRON EMISSION MEASUREMENT AND CALIBRATION

On the JET, X-mode ECE spectra are measured using a Fourier transform spectrometer (FTS). Its mirror amplitude is 15 mm with a sampling distance of 80 μm and a vibrator frequency of 30 Hz. This defines a frequency resolution of the system of 10 GHz on a frequency range between 76 and 350 GHz. On each JET pulse, a maximum of 320 interferograms is acquired. From the second optically thick harmonic, T_e profiles are then calculated and used to cross-calibrate the 96-channel heterodyne radiometer system.[3] The thermal source used for in-vessel calibration has a heated surface of 18 cm^2, an absolute radiation temperature of $\sim$810 K and a temperature uniformity of $\sim\pm$15 K. The radiation temperature is uniform in frequency except below 90 GHz where it drops to 650 K at 60 GHz. Calibration below 90 GHz is then less accurate. The last absolute in-vessel calibration of the FTS system was performed in May 1996 and has not been modified since then. Nevertheless, since 1996, frequency dependent correction using TFR pulse responses, can be applied according to the method described in Sec. II.

[a)] Electronic mail: patrick.blanchard@jet.efda.org

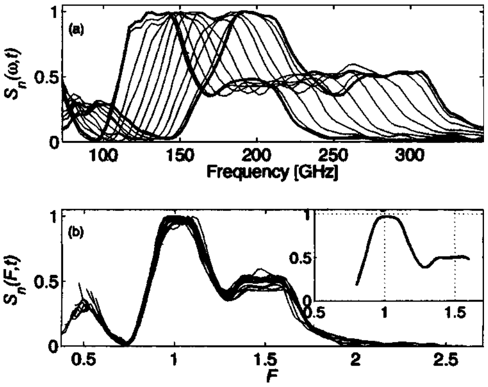

FIG. 1. (a) Some of the normalized spectra $S_n(\omega,t)$ from TFR pulse 60205. The bold spectra refer to the first and the last spectrum of the TFR. (b) Normalized spectra $S_n(F,t)$ on the normalized frequency axis F. On this scale, $F=1.5$ is the position of the third harmonic. The encapsulated curve represents the reference spectrum $S(F)$ obtained as the mean value of all the $S_n(F,t)$.

III. IMPROVEMENT METHOD

The improvement method is described in Ref. 2. Briefly, the idea is to first assume that the errors in the calibration of the FTS system are fixed in frequency and that the existing calibration curve is globally correct. $S(\omega,t)$ is the ECE temperature spectrum emitted by the plasma and defined as

$$S(\omega,t) \equiv I(\omega,t)\frac{8\pi^3c^2}{\omega^2},$$

where $I(\omega,t)$ is the spectral density of the electron cyclotron (EC) radiation at frequency ω. The frequency dependent calibration curve $C(\omega)$ is defined as $S_m(\omega,t)=C(\omega)\cdot S(\omega,t)$, where $S_m(\omega,t)$ is the measured spectrum. By varying the toroidal magnetic field during a discharge, the whole ECE spectrum moves in frequency. If the shape of the T_e profile can be held constant during the toroidal field ramp, we are then able to distinguish the errors in the profile from real spectral features.

Technically, two ohmic TFR pulses are combined to apply the correction over a wide range of frequencies. The first one with a $B_\phi(R_0)$ ramp from 3.5 to 2.3 T and the second from 2.8 to 1.7 T, where 1.7 T is deduced from the lower-frequency limit of the diagnostic. By keeping the q profile as constant as possible changing the plasma current I_p in proportion of the B_ϕ changes, the shape of the T_e profile is held constant during the pulse while its amplitude decreases due to the decrease in ohmic heating. The electron density stays mainly constant during the ramp.

As the $T_e(R,t)$ shape is constant during the toroidal field ramp, to compare the different spectra $S_m(\omega,t)$, we calculate the normalized spectrum $S_n(\omega,t)=S_m(\omega,t)/T_e(R_{0,}t)$, where R_0 is the plasma center position. In Fig. 1, we represent some of the normalized spectra obtained ruing one of our TFR pulses. The reference spectrum $R(F)$, where F is the normalized frequency $F=\omega/2\Omega_{ce}(R_0,t)$ with Ω_{ce} being the electron cyclotron frequency, is obtained as the average of the normalized spectrum mapped onto the normalized frequency coordinate $F.R(F)$ is a good approximation of the real normalized spectrum (see Fig. 1). Finally, the frequency dependent correction factors $C_1(\omega)$ are estimated as

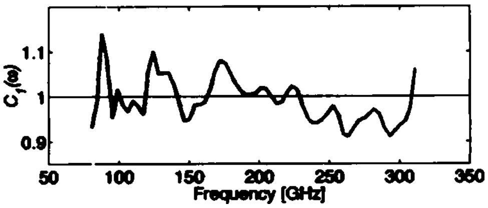

FIG. 2. Correction factor $C_1(\omega)$ obtained from pulses 60204 and 60205. The grey zone represents the standard deviation of the standard deviation of the measurement.

$$C_1(\omega) = \frac{1}{N(\omega)}\sum_{t=t_1}^{t_2}\frac{S_n(\omega,t)}{R(\omega)},$$

where $N(\omega)$ is the number of spectra during the ramp valid for the frequency ω, t_1, t_2 are the starting and ending time of the toroidal field ramp, and $R(\omega)$ is $R(F)$ mapped back onto the respective frequency scales.

As the method is valid on the optically thick second harmonic of the X-mode spectrum, the normalized amplitude of the third harmonic itself does not vary as B decreases [Fig. 1(b)]. Effectively, for these TFR pulses, the third-harmonic normalized spectrum is mainly constant during the TFR. The correction method is then applied from $F=0.8$ up to 1.6.

IV. EXPERIMENTAL RESULTS

The final correction curve $C_1(\omega)$ obtained using TFR pulses 60204 and 60205 performed in August 2003 is shown in Fig. 2. Its mean value is 1, and oscillations do not exceed 10% except at very low frequencies where the correction is the most important. The grey zone represents the standard deviation of all the correction estimations at each frequency around the mean value represented by the black line. Examples of the effect of this improved calibration on both the ECE spectra and on the T_e profiles, are shown in Fig. 3 for three different magnetic fields. First, considering the T_e profiles, the improvement in the quality of the profiles is clear as it effectively suppresses the odd oscillations appearing at specific frequencies but also improves the symmetry of the profiles. This last fact is of great importance because nowhere in the method are there any considerations of the sym-

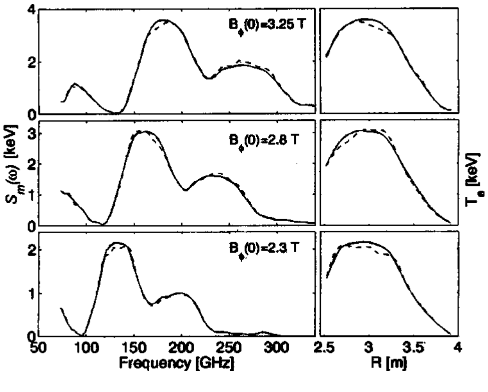

FIG. 3. Temperature spectra $S_m(\omega)$ (left column) and $T_e(R)$ profiles (right column) from pulse 60205 for three different magnetic fields. The dashed curves show the data before calibration correction while the full lines are the data after improvement.

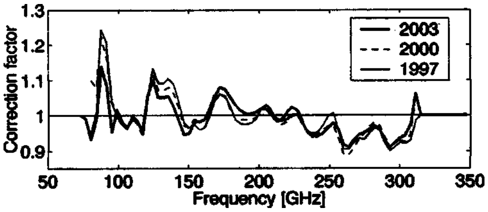

FIG. 4. FTS diagnostic response to three pairs of TFR discharges done in 1997, 2000, and 2003.

metry. More globally, the whole spectrum quality is improved as the shape correlation between second and third harmonic emission is increased.

The correction method assumes that the calibration curve is globally correct. As the last in-vessel calibration dates from 1996, checks on the validity of the FTS calibration in the long term have been made. At each JET restart, two reference TFR discharges are done and the frequency response of the FTS system is analyzed. Since 1996, about ten TFR pulse pairs have been obtained. As shown in Fig. 4, the response of the system has not changed within the 5% accepted error bars except at very low frequencies where the calibration is much more difficult due to the lower emissivity of the calibration source at these frequencies. This clearly shows that it is possible to maintain a valid calibration for a period of more than eight years without in-vessel access. This demonstrates that the calibration of such a diagnostic system can be stable over a long period which bodes well for ECE diagnostics on the International Thermonuclear Experimental Reactor.

Since the calibration correction is obtained by using only the FTS results themselves rather than using information from other diagnostics, it is also important to compare the results with another independently calibrated T_e diagnostic. In Fig. 5, we represent comparison of T_e averaged over ±10 cm around the plasma center for both ECE and Lidar Thomson scattering measurements during ohmic heating only. For the 1000 pulses before the correction, the ratio between both T_e measurements was 1.002 and it becomes 0.999 after the correction, i.e., unchanged within experimental errors. This confirms that there is no overall variation in the calibration of either diagnostics.

Of course, as the correction affects the shapes of the T_e profiles, it affects in proportion the temperature gradient ∇T_e and all measurements related to it. The dimensionless Larmor radius ρ_T^* characterizing the internal transport barrier (ITB)[4] depends on both T_e and ∇T_e. A detailed study of specific JET discharges with ITB at different magnetic fields, based on the calculation of ρ_T^* for corrected and noncorrected T_e profiles, does not show any significant influence of the correction on the emergence, location, and time evolution of the ITB.

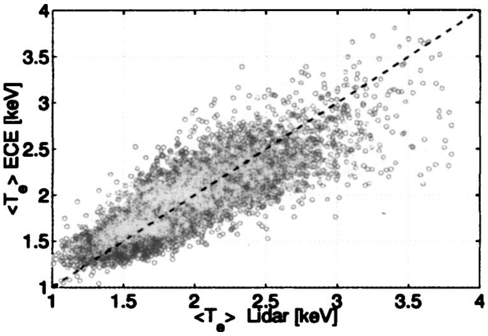

FIG. 5. Comparison of T_e averaged on ±10 cm around the plasma center for both ECE and Lidar measurements during ohmic heating only. The black circles correspond to pulses 60000 to 61000 before the correction and the grey triangle correspond to pulses 61002 to 62000 after corrections on the calibration. The dashed line represents the equality line when $\langle T_e\rangle_{\mathrm{ECE}} = \langle T_e\rangle_{\mathrm{Lidar.}}$

Finally, we have considered previous TFR pulse pairs up to 1996 and these produce the same correction factors $C_1(\omega)$ within 3%. This again confirms the reliability of the system in the long term and led us to apply the correction backward in time.[5]

ACKNOWLEDGMENTS

The authors would like to thank D. V. Bartlett for useful advice and M. Zerbini for induction to the diagnostic.

[1] A. E. Costley, E. A. M. Baker, D. V. Bartlett, D. J. Campbell, M. G. Kiff, S. E. Kissel, G. F. Neill, and P. F. Roach, *Proceedings of the Fifth Joint Workshop on ECE and ECRH* (1985), p. 3.

[2] H. Bindslev and D. V. Bartlett, JET internal report JET-R(88)04.

[3] E. Luna, Rev. Sci. Instrum. These proceedings.

[4] G. Tresset, X. Litaudon, D. Moreau, X. Garbet, and Nucl. Fusion **42**, 520 (2002).

[5] During the 2004 JET shutdown, data from radiometry and from FTS will then be reprocessed considering the improvement back to the C6 JET campaign that started in September 2002 with pulse 56584. This corresponds to the upgrade of the radiometer to 96 channels (see E. Luna, Rev. Sci. Instrum. These proceedings.)